LLNL-CONF-424063

LAWRENCE LIVERMORE NATIONAL LABORATORY

Compressible gas flow through micro-capillary fill-tubes on NIF targets-modeling and experiments

S. D. Bhandarkar, T. G. Parham, J. E. Fair

February 18, 2010

19th Target Fabrication Meeting
Orlando, FL, United States
February 21, 2010 through February 26, 2010

Compressible gas flow through micro-capillary fill-tubes on NIF targets- modeling and experiments

Presentation at the

19th Target Fabrication Meeting

Feb 25th, 2010

Suhas Bhandarkar,

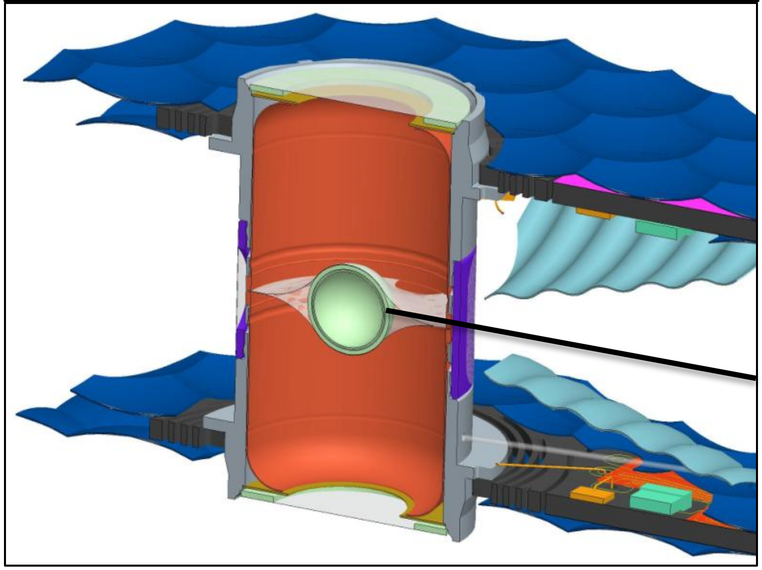
Tom Parham, Jim Fair

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

NIF targets have two separate chambers (capsule/hohlraum) which are pressurized using filltubes

- **Fill tubes supply gases to the two chambers – capsule and hohlraum**
  - — Capsule fill tube specification: 5µm inner dia
  - — Small volume
- **Fill tubes need to be about 115mm long and be flexible**
- **Hohlraum filltubes**
  - — 75µm ID x 150µm OD polyimide coated silica capillary
- **Composite tube for capsule**
  - — Majority of length is 30µm ID x 150µm OD polyimide coated silica
  - — A 5µm borosilicate capillary penetrates the capsule to meet the physics specs

Cross-sectional view of NIF Cryogenic Target



Impedance to flow due to the small diameters of the capillaries presents a few challenges

Importance of Response Time

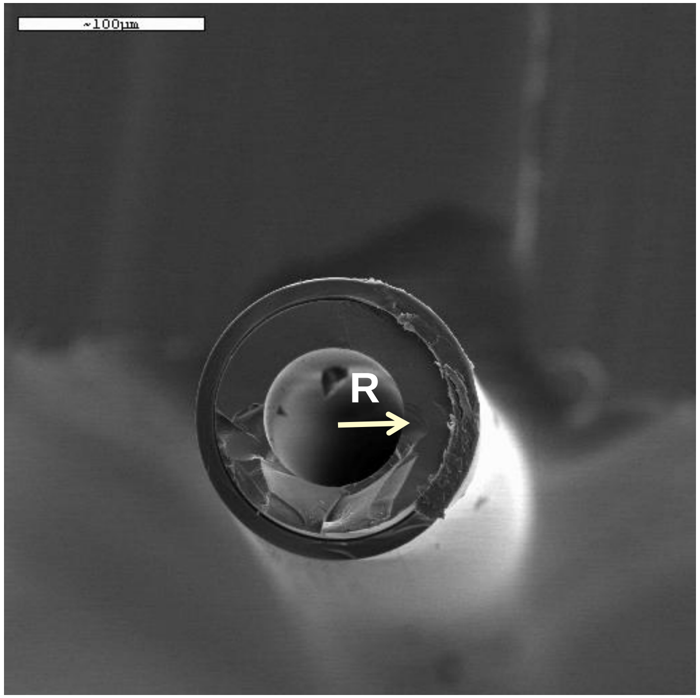
- **Knowing the changes in pressure and composition inside the capsule or hohlraum due to temperature or pressure variations on the outside**
- **Sharp pressure differentials across the hohlraums can stretch or damage 500nm thick LEH windows**
- **Condensation of ice or debris on the inside can easily plug the capillaries**
- **Flow of permeated tritium out of the hohlraum**

LEH window

Extending the Hagen Poiseuille equation for compressible fluid flow through a tube

Limit to:

- **Low Reynolds number regime**
  - **Fully developed laminar flow**
  - ***Small β =R/L (inner radius/length)***
- **Small pressure drops**
  - ***Small ε =(P_0-P_L)/P_0*, where P_0 & P_L are pressures at lengths 0 and L**
  - **In the limit, we get Hagen-Poiseuille equation**
- **Chose a perturbation based solution by Prud'homme et al***



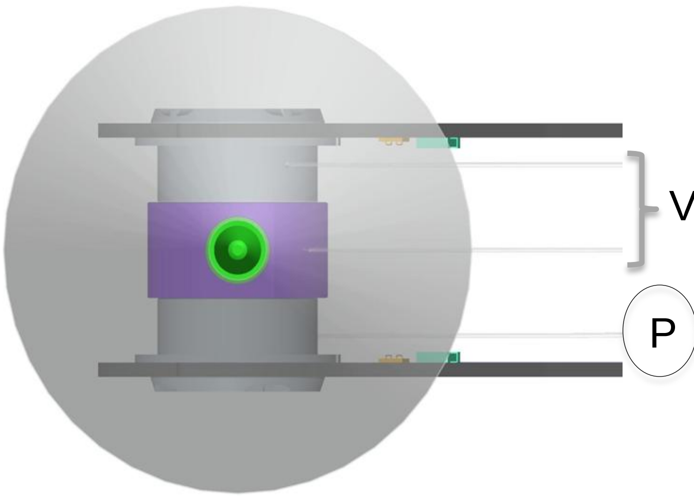
Volumetric flow-rate Q:

$$Q = \frac{\pi(P_0 - P_L)R^4}{8\mu L}[1 - \frac{1}{2}\varepsilon - (0.02919\,\kappa)\varepsilon\beta + (0.02919\,\kappa)\varepsilon^2\beta + (\frac{2}{3} + 0.00227\,\kappa^2)\varepsilon^2\beta^2 + ...]$$

where μ is viscosity, ρ_0 is the mass density at P_0 and $\kappa = R^3\rho_0(P_0 - P_L)/L\mu$

***Ref: Prud'homme et al, App Sci Res., 43, p67 (1986)**

We are interested in the gas composition and pressure in the two chambers within the target

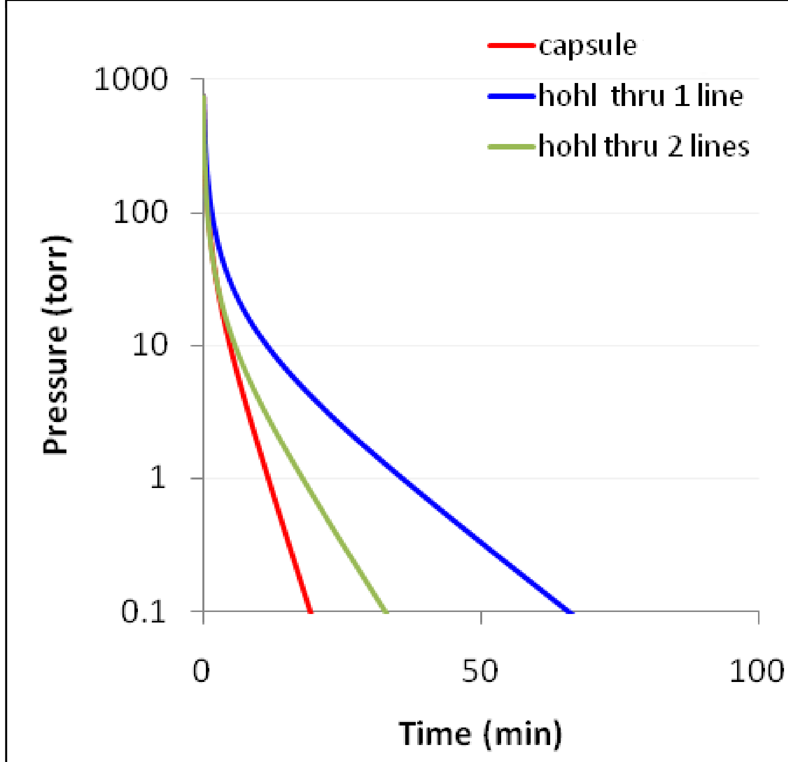


For a chamber with volume V_c *at pressure* P_c *and containing* n_c *moles:*

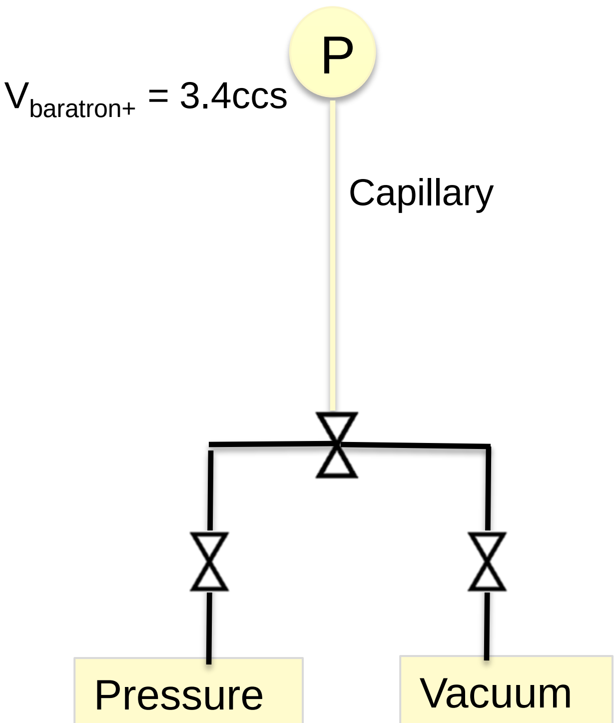
$$\frac{dn_c}{dt} = \frac{n_c(t)}{V_c} Q(n) \quad \text{or} \quad \frac{dP_c}{dt} = \frac{P_c}{V_c} Q$$

$$\ln(P_c) + Const = \frac{Q}{V_c} t$$

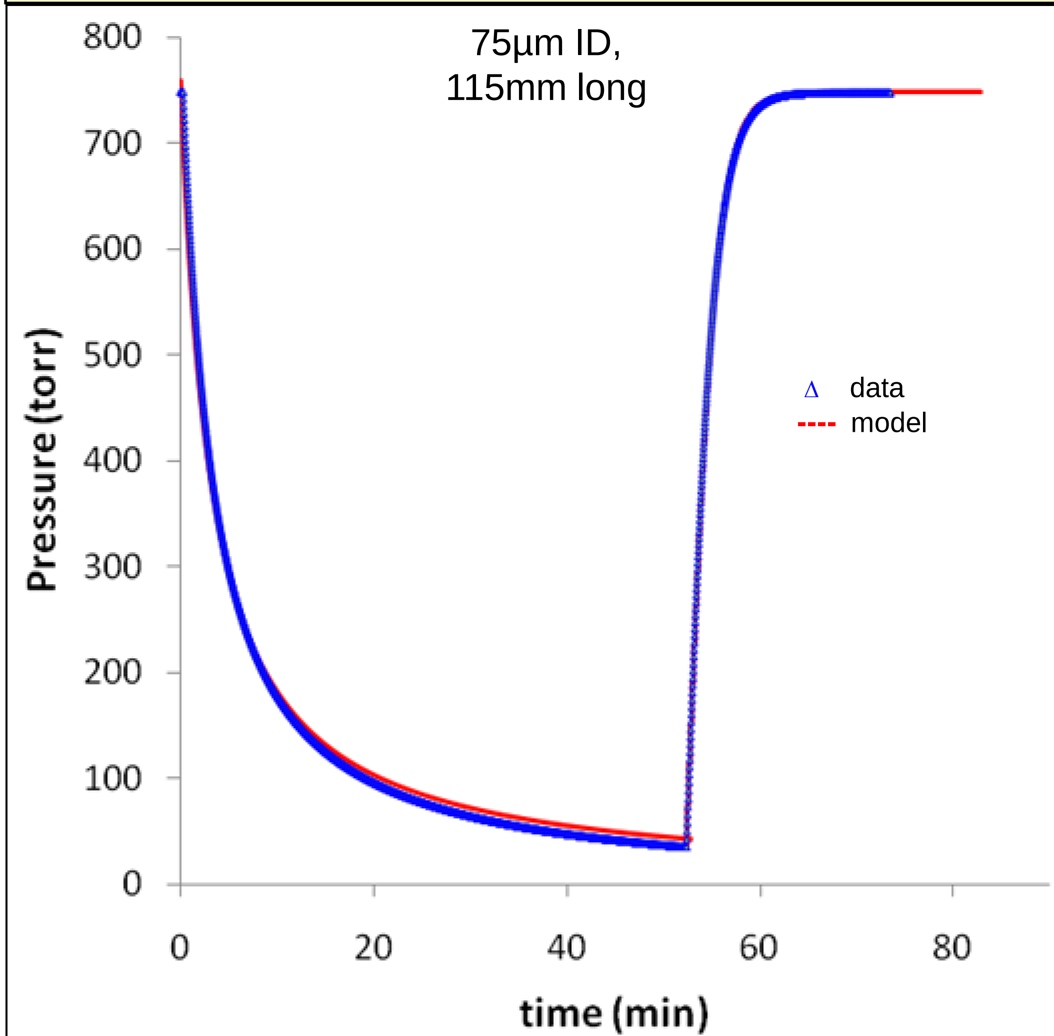
Evacuation of air from target: Pressure vs time profile



A baratron with a fixed known volume can be used to generate pressure vs time data to verify model

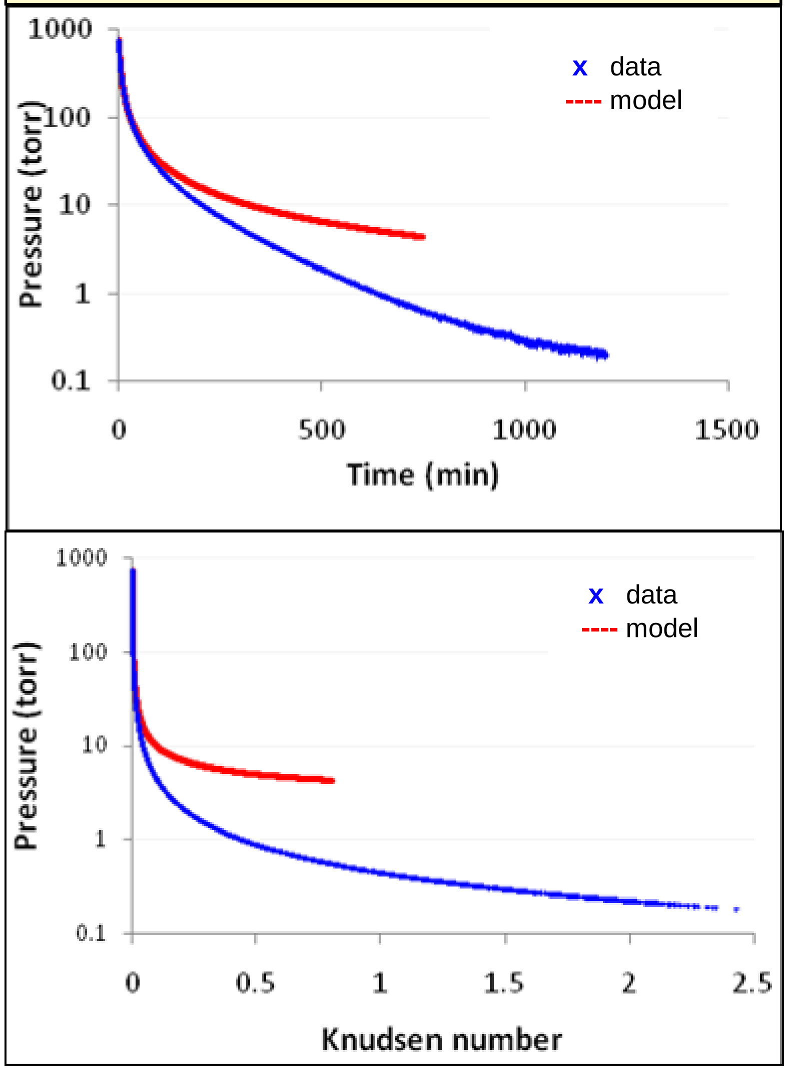


Pressure: measured data vs simulation



Transition region between continuum flow and free molecular flow

Deviation at low pressure



- **Continuum flow model deviates at K_n (Knudsen number) of about 0.005**
  - **— K_n is the ratio of molecular mean free path λ to capillary diameter D**
- **K_n is no high enough to consider free molecular flow, instead points to transition region**
- **Deviation increases with increasing K_n**
  - **— Model that account for transition flow using K_n**

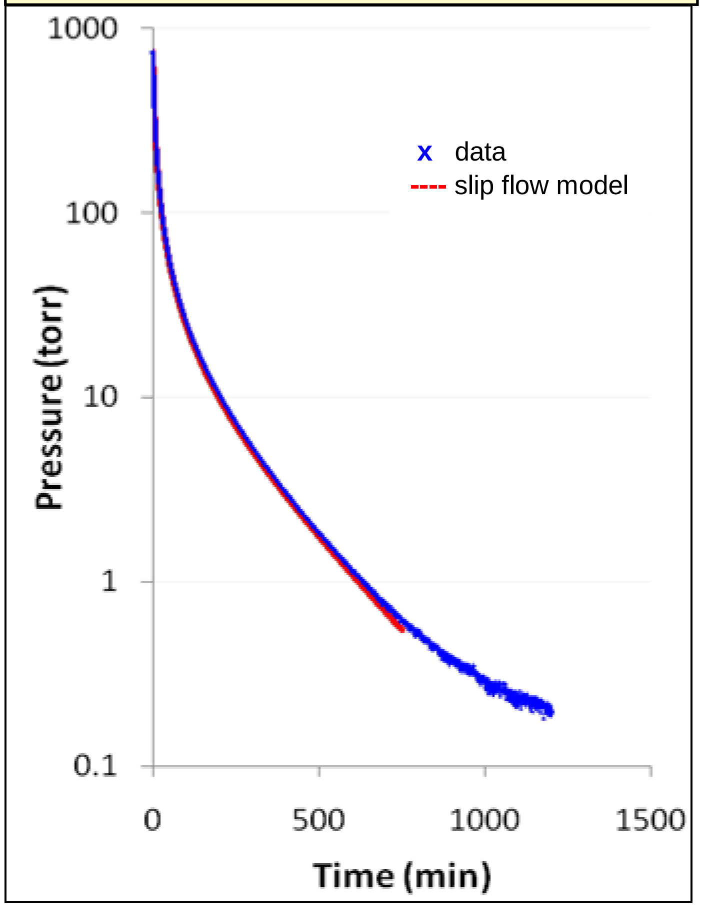
Slip flow model for flow behavior at low pressures before onset of free molecular flow

- Viscous flow uses a no slip boundary condition at the wall
  - But Navier Stokes equation ceases to be valid as $K_n > 0.01$
- For free molecular flow (neglect intermolecular collisions), incident and reflected tangential velocities are equal
- In between, invoke a slip flow model, with a small but non-zero tangential wall velocity

$$Q = \frac{\pi(\Delta P)R^4}{8\mu L}\left[1 - \frac{1}{2}\varepsilon - (0.02919\kappa)\varepsilon\beta + \ldots\right]\left(1 + 4\left(\frac{2}{f_s} - 1\right)\right)\frac{\lambda}{R}$$

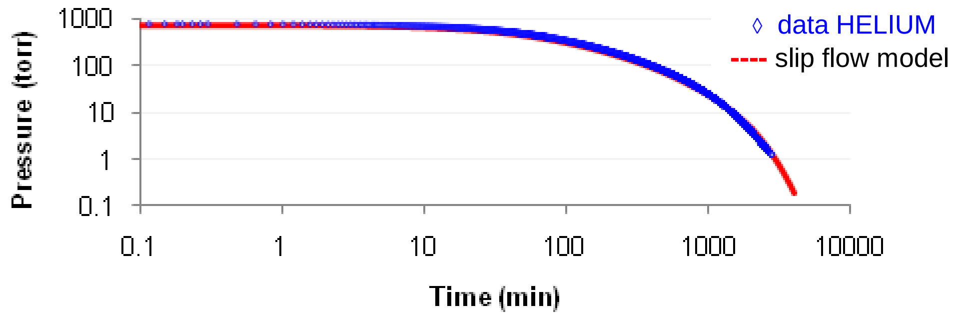
where f_s is the fraction of molecules impinging on the walls of the tube

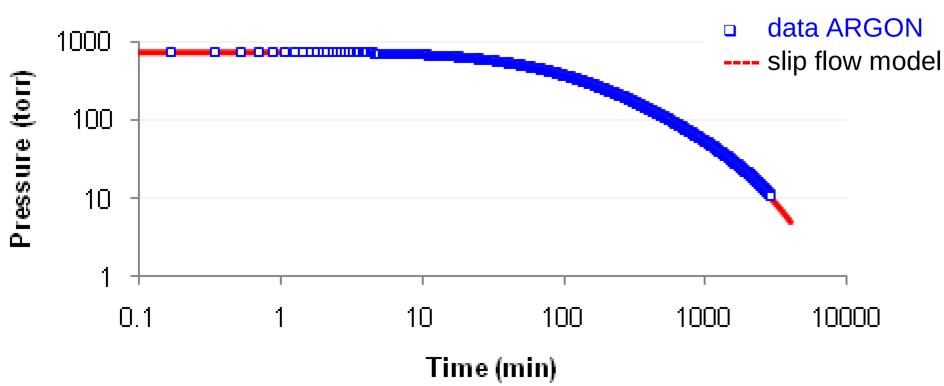
Using slip flow equation

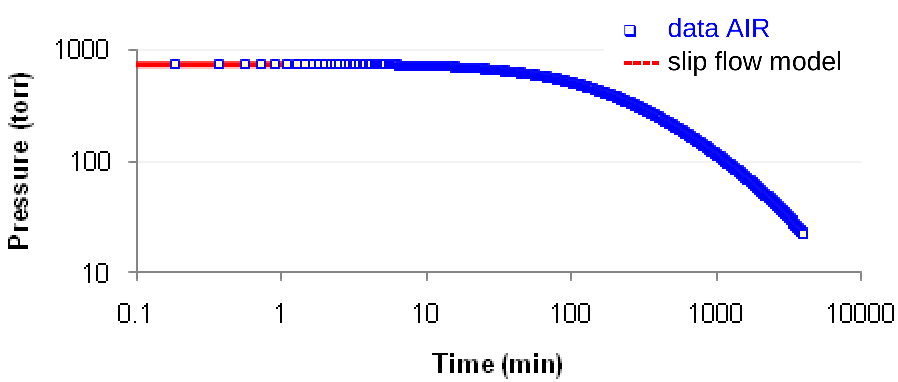


F Sharipov & V. Seleznev, *J. Phys. Chem. Ref. Data* 27 , p657 (1998)

Unraveling slip flow parameters – effect of molecular diameter





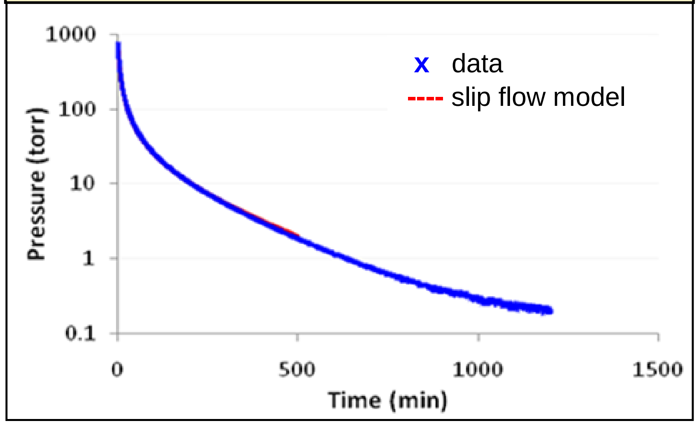


- **Slip flow has two parameters that need to be specified**
  - **f_s,**
  - **hard sphere molecular diameter d, for calculation of λ**
- **Since air is mixed fluid, d is best specified for single component gases**
- **We find that f_s is constant**

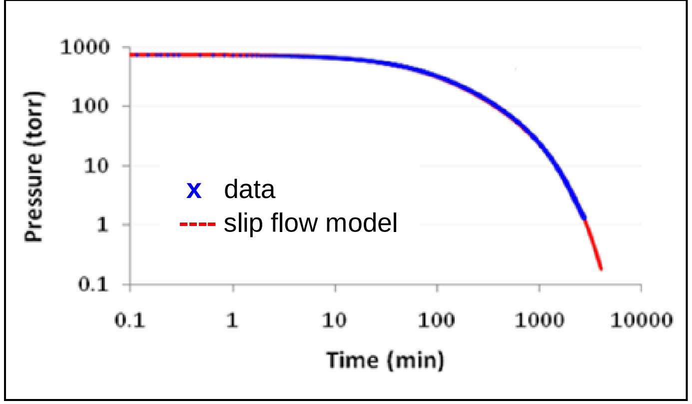
	d (A)	fs
He	2.56	0.43
Ar	4.0	0.43
Air	4.57	0.43

Some important conclusions from application of slip flow model to the capillary flow data

75µm, 115mm long capillary



30µm, 92mm long capillary

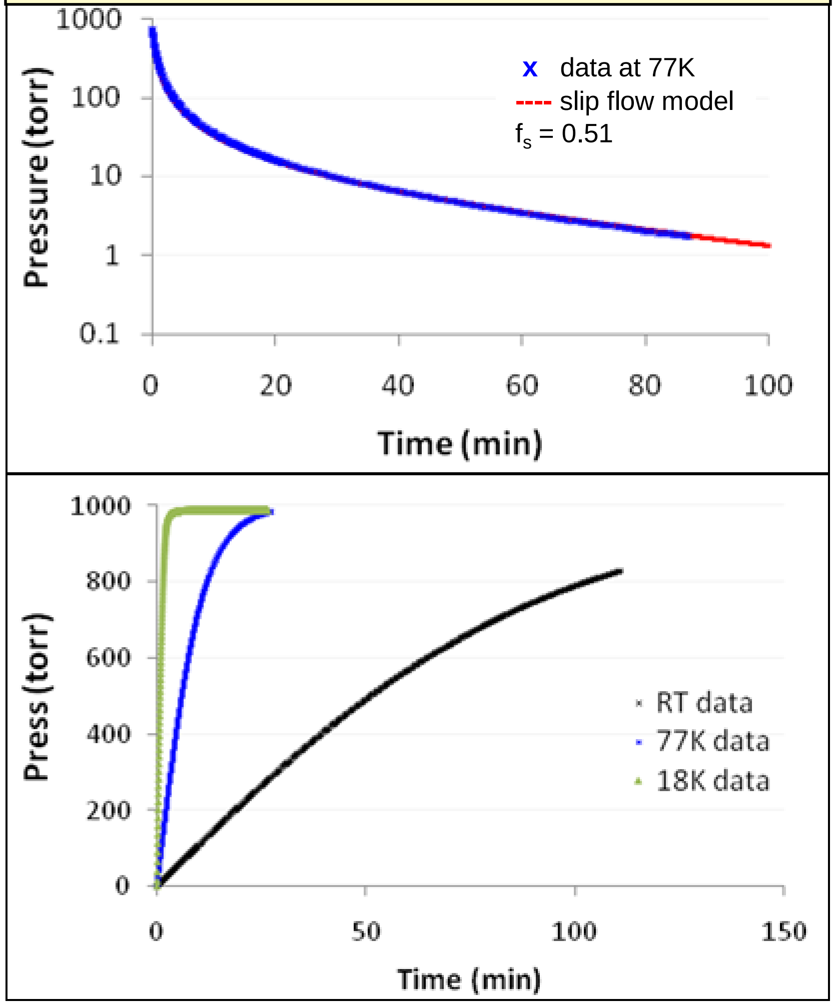


- **fs, the fraction of molecules impinging on the walls of the tube is consistently 0.43 @ RT**
  - **For capillaries of different dia**
  - **For different gases**
- **Slip flow model fits the data for a large range of K_n**
  - **from 0.005 to 18**
  - **at higher K_n, it approaches free molecular flow**
- **Data here indicates that conventional free molecular flow equation (K_n>1) over-predicts the flow**

Slip flow model can be used for flow at cryogenic temperatures as well

- **Gases flow faster at lower temperatures as**
  - — Lower viscosity
  - — Greater density
- **Model takes into account two temperature zones**
  - — RT for baratron
  - — Cryogenics temp for the capillary
- **Viscosities from NIST for Helium can be used get an exact fit to the cryogenic data**

Capillary flow of He at cryogenic T



Accounting for changing radii

- **Filltubes used on NIF targets are combinations of tubes of different diameters and lengths**

- **For a conical tube, with inner radii R_0 and R_L and length L:**

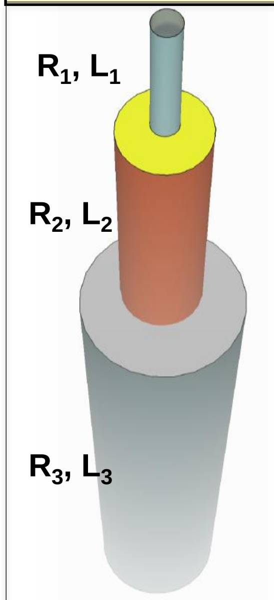
$$R_{eff} = R_0 \left[\frac{3\alpha^3}{1+\alpha+\alpha^2} \right]^{0.25} \quad \text{where } \alpha = R_0/R_L$$

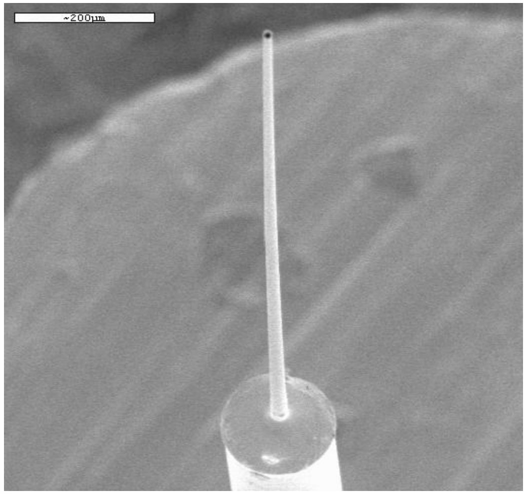
- **For two tubes of inner radii R_1 and R_2 and lengths L_1 and L_2:**

  Let $x = L_2/L_1$; then

$$Q = \frac{\pi(\Delta P)R_1^{\,4}}{8\mu L}\left(\frac{x}{R_2^{\,4} + xR_1^{\,4}}\right)\left[1 - \frac{1}{2}\varepsilon - (0.02919\kappa)\varepsilon\beta + (0.02919\kappa)\varepsilon^2\beta + \ldots\right]$$

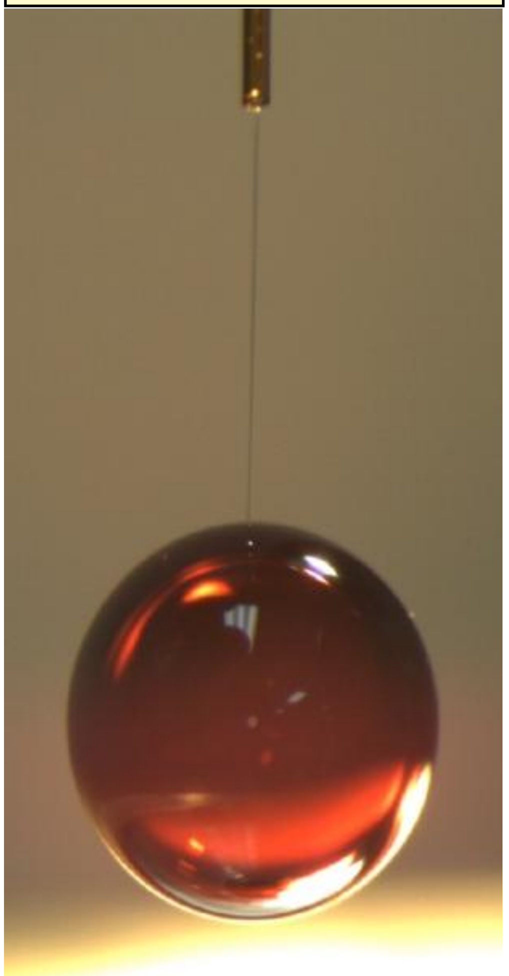
Fill tubes on NIF targets are made up of multiple capillaries



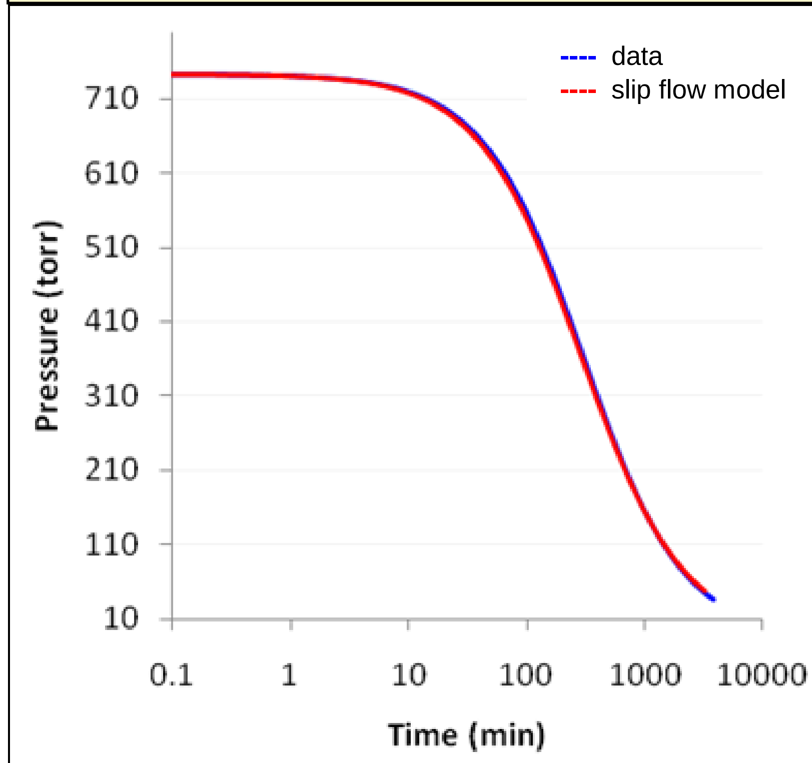


Verification of the model for composite and conical tubes

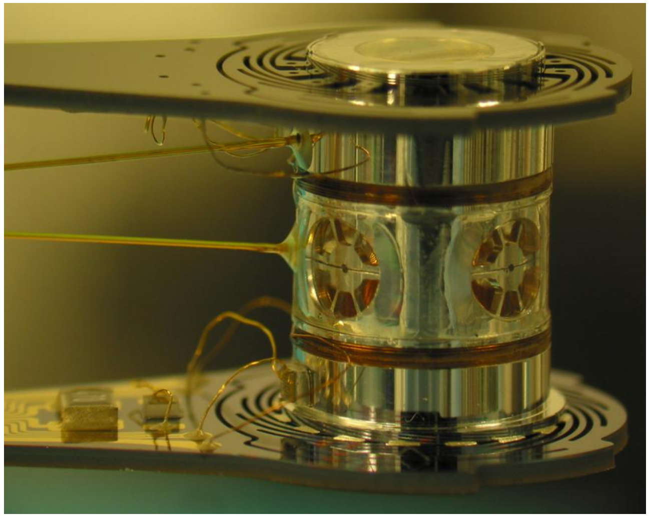
Composite fill-tube for capsule



Composite tube- data vs model



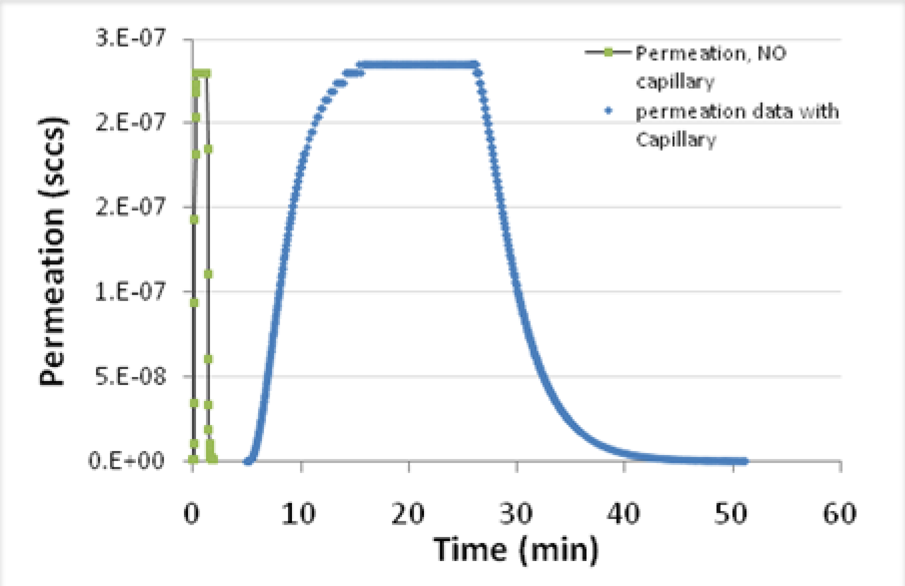
Model can be used to predict rate permeation of He from the polymeric films on the target

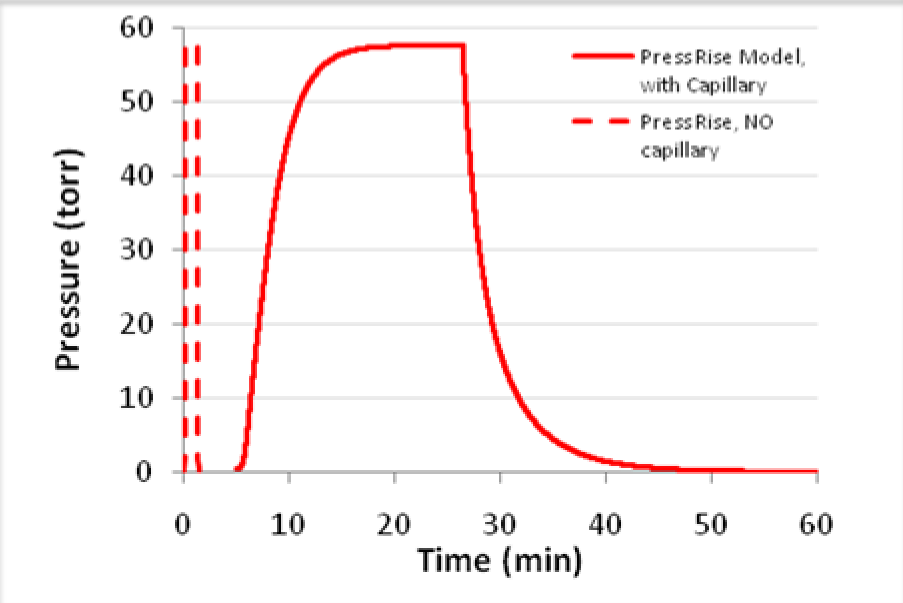


- **Permeation depends on pressure**
  - **Pressure depends on capillary conductance**

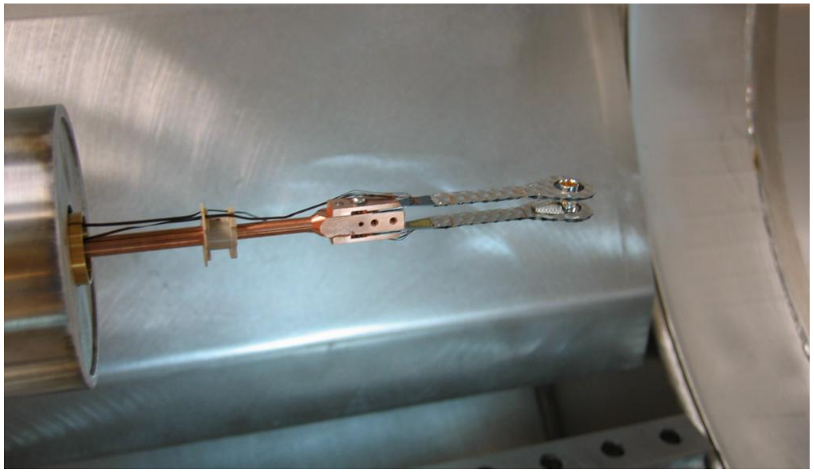
- **Permeation is instantaneous compared to filling through capillary**

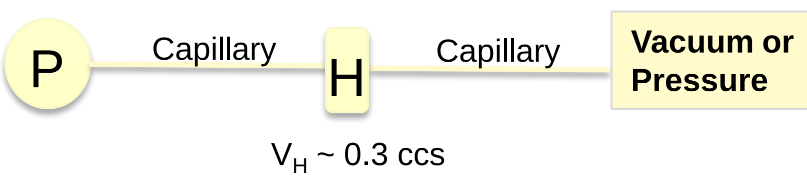
Permeation rate of He from TMP





Extending the model to a dual chamber system allows prediction of the return line pressure

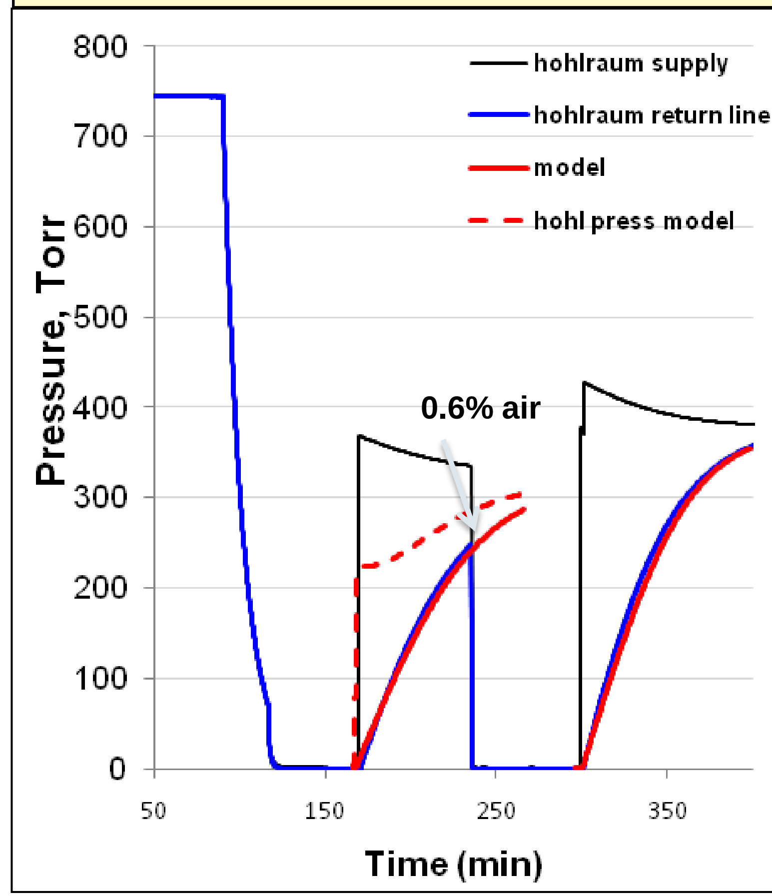




Cascading flow model

- **Once the volumes are known, we can accurately model the return line pressure and therefore the conditions in the hohlraum**

Data from target on NIF



Summary

- Model has been set-up and validated to predict the flow through micro-capillaries
  - Covers the range of pressures
    - Continuum to molecular flow
  - Accounts for composite capillaries connected to a series of chambers
  - Extends to cryogenic temperatures

- Data suggests that
  - Modified Hagen Poiseuille equation can be used for simulating viscous flow of compressible fluids for low ΔP
  - Slip flow extends to Knudsen numbers to at least 18
  - Data yields a consistent fraction of molecules reflecting specularly from the walls- 0.43 to 0.51

- This can be used to predict the hohlraum and capsule pressures and compositions for various external perturbations


NIC